

Digital micromirror array for projection TV

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A light modulator for high-definition projection television systems has been constructed using an array of micromirrors. Thin-film and surface micromachining technology provide the primary means of fabrication for the array, which is built up over conventional CMOS SRAM address circuitry. This article provides details of the manufacturing process.

A reflective, spatial, light modulator composed of an array of rotatable aluminum mirrors has shown promise as an alternative to LCD technology for standard and high-definition projection television (PTV) systems. Results demonstrate that the modulator, called a digital micromirror device (DMD), offers performance equal to or better than a cathode ray tube. Fundamentally, the DMD is an advanced microelectromechanical system (MEMS) that utilizes a mature address circuit technology. It offers potential as a display device (Fig. 1) that can be manufactured with high yield at marketable cost [1,2].

Micromirror and DMD array

Figure 2a illustrates the micromirror element, an aluminum mirror suspended over an air gap by two thin, post-supported, mechanically compliant torsion hinges that permit a mirror rotation of $\pm 10^\circ$. The posts are electrically connected to an underlying bias/reset bus (Fig. 2b) that connects all the mirrors of the array directly to a bond pad. Fabricated over address circuitry consisting of conventional CMOS SRAM cells, the reflecting elements individually consist of mirrors $16\text{ }\mu\text{m}$ wide on a pitch of $17\text{ }\mu\text{m}$ (Fig. 3). In this manner, a bias/reset voltage waveform can be applied to the mirrors by an off-chip circuit. Below each mirror are a pair of address electrodes, which are connected to the complementary sides of the underlying SRAM.

Figure 4 shows the layout of the integrated DMD structure. The SRAM underlying each mirror is a conventional six-transistor circuit or storage cell fabricated using a twin-well CMOS, $0.8\text{-}\mu\text{m}$, double-level metallization process. Depending on the SRAM state, a combination of the bias and address voltages electrostatically attracts each mirror element to one of the address electrodes.



Figure 1. Digital micromirror reflecting array. CMOS SRAM cells exist underneath each individual micromirror (pixel). *Original image by Steve Kelly.*

The mirror rotates until its tip touches a landing electrode that is held at the same potential as the mirror. A "1" in the memory cell rotates the mirror $+10^\circ$, while a "0" causes a rotation of -10° . Although the DMD can be operated in an analog mode, the mirrors are biased so that only the digital landing states of $\pm 10^\circ$ are possible. This digital operating mode permits use of low-voltage CMOS circuits and ensures large, uniform deflection angles.

Projection TV system

Figure 5 illustrates the operation of a single-chip, DMD-based PTV system. A condenser lens collects light from a white light source, e.g., a metal halide or xenon arc lamp. The illumination is directed at a $+20^\circ$ angle from the normal to the DMD surface and orthogonal to the rotational axes of the individual mirrors of the array. A lens located above the chip projects an enlarged image of the DMD on a screen. When rotated at $+10^\circ$, the individual mirror

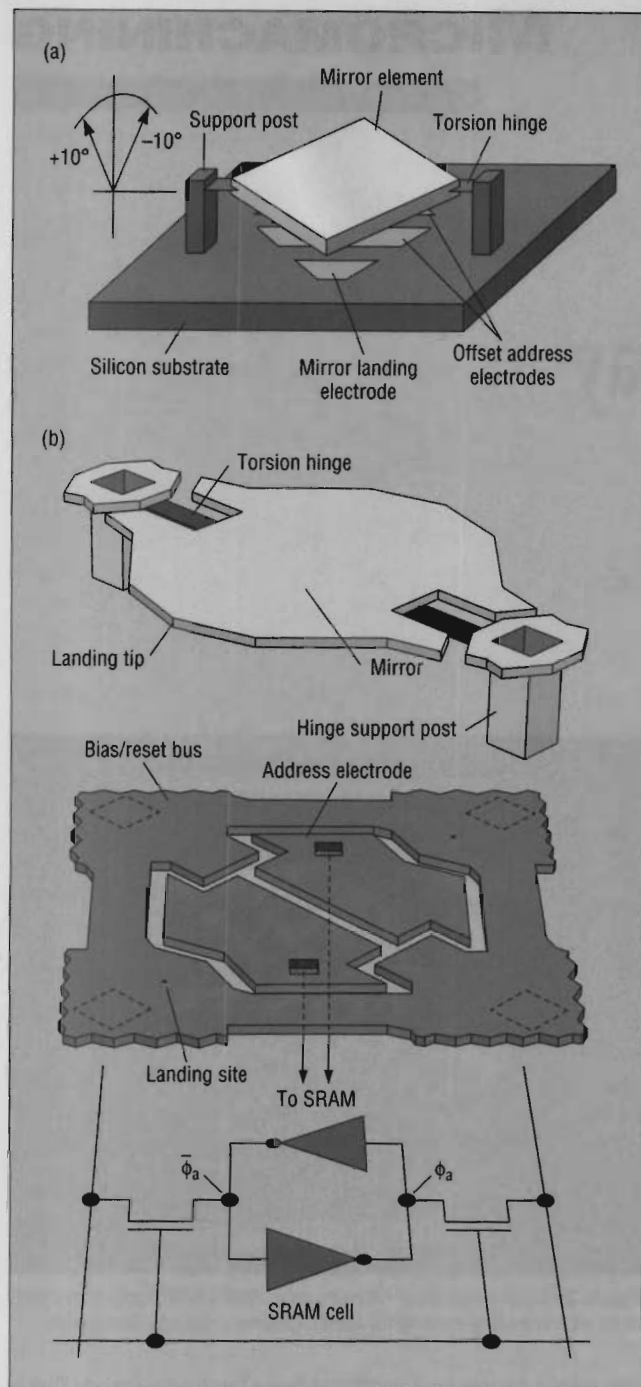


Figure 2. (a) Digital micromirror element with conventional torsion hinge suspension, and (b) mirror configuration with schematic of the SRAM cell.

elements reflect incoming light into the projection lens pupil to produce a bright image on the screen. When rotated -10° , the mirror elements appear dark. Light reflected, scattered, or diffracted into the optical path by the hinge or mirror support posts increases the illumination level during a DMD pixel-off condition and reduces the projection system's contrast ratio.

Since mirror response time is fast ($\sim 10 \mu\text{s}$), gray scale output can be realized with the DMD by employing pulsewidth modulation of the mirror output. In this case, each video field is subdivided into time intervals or bit times. For example, an 8-bit modulation scheme enables 2^8 or 256 gray levels [3].

The PTV system can utilize either a single- or a three-chip DMD

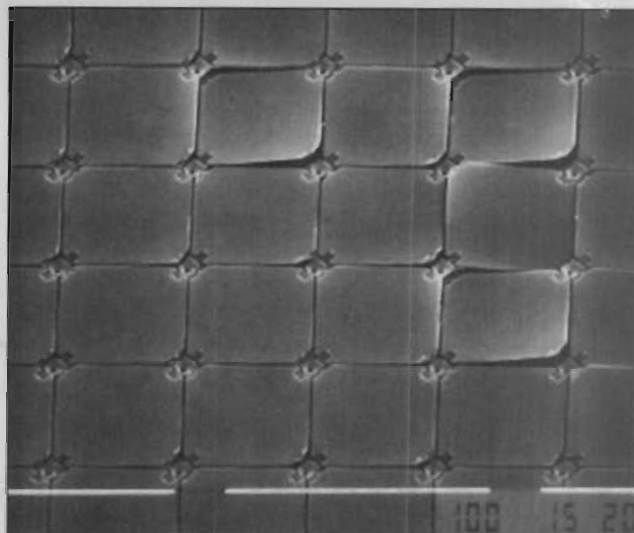


Figure 3. A portion of a DMD array showing selected mirror elements deflected.

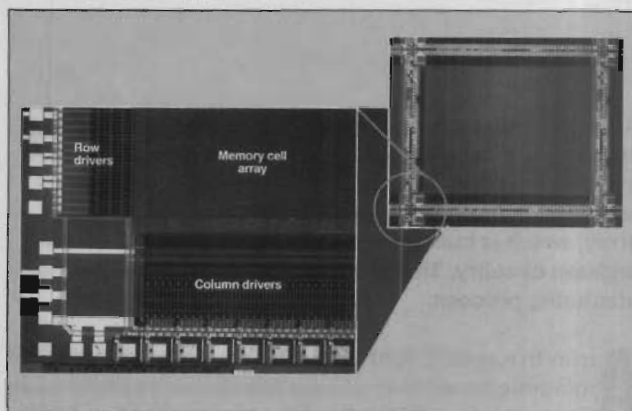


Figure 4. DMD memory array module and package.

arrangement. In a three-chip system, each chip is used for one of the primary colors—red, green, or blue. This is analogous to systems employed in most LCD projection displays. However, a single-chip system is also practical because of the DMD's high light efficiency. In this case, a color wheel may be used to sequentially illuminate the DMD with the three primary colors. The single-chip approach is less expensive and provides pixel self-convergence. The most recent DMD device, a 768×576 pixel array with 442,368 mirrors, has been demonstrated in both one- and three-chip PTV systems with projection screen diagonals ranging from 42 in. to 13 ft.

Surface micromachining

Four photolithographically defined layers are surface micromachined to form the electrode, sacrificial layer, hinge, and mirror. The sacrificial layer is an organic material that is plasma-ashed to form the air gap between the address electrodes and mirror. The other three layers are formed from dry plasma etched, sputter-deposited aluminum. Structural details and the fabrication sequence are shown in Fig. 6.

DMD surface micromachining begins after contact openings for the address circuit electrode have been formed in the circuit's protective oxide. The address electrode film is then sputter-deposited onto the oxide, lithographically patterned, and plasma etched. An organic sacrificial planarizing layer is then spun over

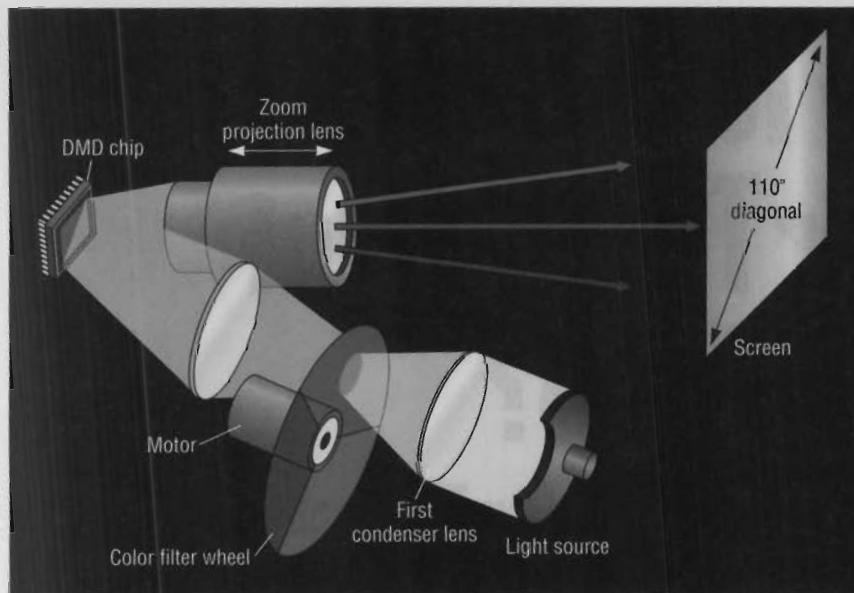


Figure 5. DMD single-chip color projection display.

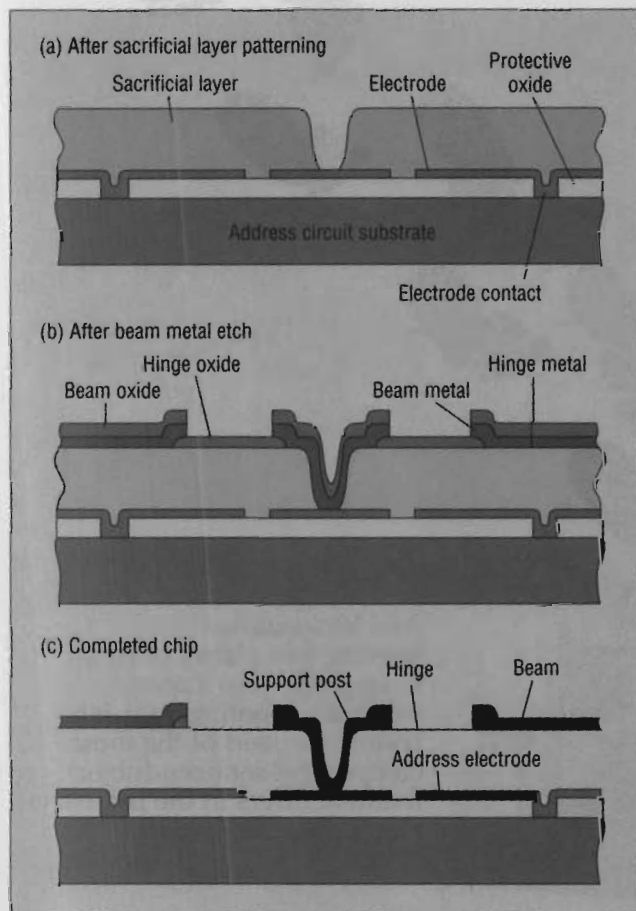


Figure 6. Mirror element fabrication sequence.

the electrode and patterned with vias, which will be used subsequently to form the support posts. Standard IC technology tightly controls the critical dimensions in the *x* and *y* directions. However, the *z*-axis dimension (i.e., thickness) must be equally tightly controlled to achieve reproducible, uniform mirror tilt angles.

Two metal layers are employed for the buried hinge process.

The hinge aluminum alloy sputtered on top of the sacrificial layer is followed by a plasma-deposited masking oxide that is patterned to define the hinges. Deposition of a second aluminum alloy layer then buries the hinge oxide and forms the beam. This, in turn, is followed by still another plasma-deposited masking oxide, which is patterned to form the mirrors. The support posts consist of both the hinge and mirror metals.

Finally, a single aluminum plasma etching step patterns the hinges and mirrors. The mirror metal overlying the hinge region is etched away to expose the buried-hinge oxide, which functions as an etch stop. When the aluminum plasma etching has been completed, what remains are regions of hinge and mirror metal that have been simultaneously patterned [4].

Recently a "hidden hinge" structure has been employed (Fig. 7). This enables fabrication of a pixel array with a compact, closely spaced set of square mirrors that provide high optical contrast ratio and efficiency; the hinges and their associated support posts are hidden under the mirror. A mirror support post connects the mirror to an underlying yoke, and torsion hinges connect the yoke to hinge support posts. With this particular architecture, the hinge and the address and landing electrodes are coplanar.

The hidden hinge architecture requires two sacrificial layers—one between the mirror and the underlying hinges and address electrodes, and a second between the coplanar address electrodes and hinge and the underlying third level of metal that is in contact with the CMOS SRAM structure.

Light diffraction is significantly reduced and the projection system's contrast ratio is improved when the hinges and support posts are hidden under the mirror. The mirror edges at the landing tip are orthogonal and the landing tip diffracts less light, so that degradation in the contrast ratio is reduced. Increased mirror area promotes greater optical efficiency [5].

Back-end assembly

It is during back-end operations that the DMD device finally becomes functional. This occurs upon removal of the sacrificial layer. During the preliminary wafer sawing step, it is important that individual chips not be contaminated with particles, which can interfere with the DMD's mechanical operation and can produce defects associated with light scattering. When wafer sawing is complete, the chips are placed in a plasma etching chamber, where isotropic etching creates an air gap by removing the sacrificial layer from under the mirror and hinges.

Once the DMD mirrors are mechanically released, their operation can be tested and DMD assembly can begin. The entire assembly process requires a cleanroom environment and particle monitoring. Packaging is an important consideration, since the package not only provides signal and power lead connections to the chip, but also provides protection from the outside environment.

Although a familiar sequence of assembly operations is employed for the DMD—die attach, wire bond, window seal, and final test—the structure nevertheless requires special handling. Front-side, pick-and-place contact collets will damage the DMD's mirror array, and particulate contamination can cause

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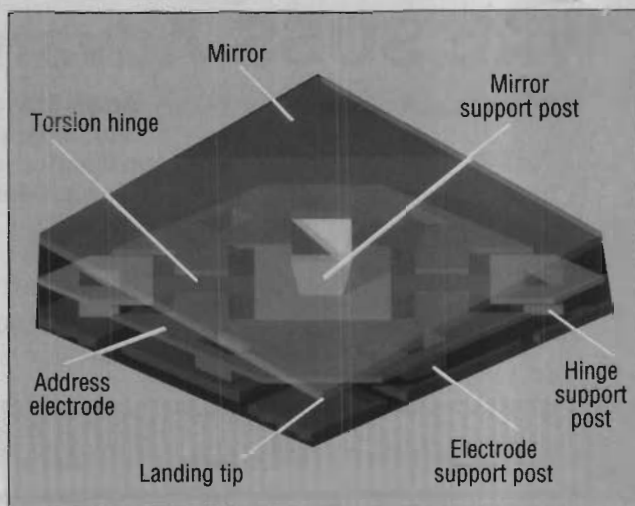


Figure 7. DMD hidden-hinge structure.

numerous problems. Special attention must be given to particle control and device handling during each assembly operation. The die attach and window sealing processes must utilize adhesives with low outgassing properties, since adhesive outgassing can promote mirror stiction. A robust package is also required to maintain a proper ambient environment for the chip. In some cases, chip cooling may be necessary.

Summary

A micromirror array — the light-modulating element of a PTV system — has been surface micromachined on top of conventional CMOS SRAM address circuitry to form a DMD. The electrodes, hinges, posts, and mirrors comprising the DMD's superstructure are formed in a multilayer thin-film stack, which includes a sacrificial layer that is removed by plasma etching during back-end assembly. Special attention is required to avoid particle contamination during fabrication and device assembly. ■

References

1. Jack Younse, *IEEE Spectrum*, "Mirrors on a Chip," Nov. 1993.
2. L.J. Hornbeck, "Deformable-Mirror Spatial Light Modulators," *Spatial Light Modulators and Applications III, SPIE Critical Reviews*, vol. 1150, p. 86, Aug. 1989.
3. J.B. Sampsel, "An Overview of Texas Instruments' Digital Micromirror Device (DMD) and Its Application to Projection Displays," *Society for Information Display International Symposium Digest of Technical Papers*, vol. XXIV, p. 1012, May 1993.
4. J.M. Younse, D.W. Monk, "The Digital Micromirror Device (DMD) and Its Transition to HDTV," *Proc. of 13th International Display Research Conference* (Late News Papers), p. 613, Aug. 31 - Sept. 3, 1993.
5. C.E. Tew et al., "Electronic Control of Digital Micromirror Device for Projection Displays," *Int'l. Solid-State Circuits Conference (ISSCC)*, San Francisco, 1994.



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